JRS Dynamic Rollover Occupant Protection Tests of Five Contemporary Light Trucks with Hybrid III Dummies

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We conducted Jordan Rollover System tests of five contemporary light trucks. The tested vehicles were selected from a list of vehicles that the National Highway Traffic Safety Administration had tested using its static test as part of its rulemaking to amend Federal motor vehicle safety standard 216. The vehicles had FMVSS 216 roof crush strength-to-weight ratios (SWR) ranging from 2.1 to more than 4.6. The results showed only a very rough correlation between the results of the two tests. The dynamic testing gave important new insights into rollover roof performance and occupant injury potential such as the role of vehicle geometry and the importance of roof strength in reducing ejections. The dynamic tests also showed that currently available light trucks provide a wide range of rollover occupant protection performance. This program also provided initial confirmation of a new procedure for using a Hybrid III dummy to measure the potential for restrained occupant injury in a rollover.

Tests of contemporary light trucks (four utility vehicles or SUVs and one pickup) on the Jordan Rollover System (JRS) have demonstrated why dynamic testing is the only accurate way of determining rollover occupant protection for both Federal standards and consumer information programs. Such testing shows specific vehicle roof weaknesses and detailed failures that could inflict serious injuries on restrained occupants from roofs that have high strength-to-weight ratios (SWR) in Federal motor vehicle safety standard (FMVSS) 216. It also showed that one vehicle with a modest SWR gave better than expected dynamic rollover occupant protection performance. The dynamic tests also show that vehicles with similar SWR can have substantially different responses in the more realistic dynamic test conditions.

The tests of five light trucks included only one with a FMVSS 216 SWR greater than 2.6. Among the four trucks with similar SWR – 2.1 to 2.6 – there were substantial differences in performance that were not consistent with their SWR ranking.

Federal Standards on Rollover Occupant Protection

The National Highway Traffic Safety Administration (NHTSA) has issued an electronic stability control (ESC) standard that will have a significant impact on the number of rollovers. However, ESC is expected to cut the number of light truck rollovers by only about one half. NHTSA has shown no enthusiasm for promulgating standards or a consumer information program to reduce occupant casualties when rollovers occur. NHTSA again postponed issuance of a final rule to no earlier than April 2009.

It has been eight years since the agency requested comments on the need for upgrading FMVSS 216 and twenty years since it found the current roof crush standard to have been ineffective.[1] Yet in that time, the agency has not seriously considered dynamic testing for rollover occupant protection. Based on its proposals, the amended standard will probably require only a trivial upgrade to, at best, a level roughly equivalent to what was originally proposed in 1970 before it was degraded at GM and Ford's urging in the final 1971 rule (see Appendix B).

Rollover occupant protection is the last major area to be seriously addressed by NHTSA. Frontal and side impact injuries are now covered both in Federal standards and in New Car Assessment Ratings using dynamic tests with anthropometric dummies to measure injury potential. Manufacturers have responded with extensive material and technological changes to reduce the potential for injury in frontal and side impacts. At present, however, beyond the basic protection offered by safety belts and interior padding, the only rollover occupant protection standard for passenger cars and light trucks is the completely inadequate, static roof crush resistance standard, FMVSS 216.

In 2001, NHTSA asked for comment on how that standard could be improved, and in August 2005, after ignoring most of the comments, NHTSA proposed a minor upgrade of the quasi-static test standard. The proposal would have raised the roof crush resistance SWR from 1.5 to 2.5 and made residual headroom a key factor in determining compliance. It appears that only three of the five cars we tested, and one of the trucks, could meet the proposed requirement with a reasonable margin of performance. NHTSA estimated that the change would have saved only 13 to 44 lives per year – about one out of 200 rollover fatalities. In 2008, the agency supplemented the rulemaking record with the results of 26 two sided static tests, and proposed a sequential two-sided roof test and implied that the standard might be set above a SWR of 2.5.

The Insurance Institute for Highway Safety (IIHS) has now issued two reports showing a strong statistical correlation between roof strength, as measured by FMVSS 216, and reduced occupant injury in rollovers. The IIHS results suggest that the NHSA proposed upgrade of the standard would save hundreds of lives. IIHS recently announced that no vehicle will receive a "good" safety rating unless it has an FMVSS 216 SWR of at least four.[2] It is ironic that one of the better performers in our tests, the 2007 Honda CR-V, would be excluded from receiving a "good" rating. The Honda CR-V performed nearly as well as the 2007 Toyota Camry, which had an SWR of 4.3.

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1 Kahane, Charles J., "An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars – Federal Vehicle Safety Standards 206 and 216, NHTSA Technical Report No. DOT HS 807 489, Washington, D.C., 1989.

2 Brumbelow, Matthew L., Eric R. Teoh, David S. Zuby, and Anne T. McCartt, *Roof strength and injury risk in rollover* crashes, Insurance Institute for Highway Safety, Washington, D.C.: March 2008. Brumbelow, Matthew L., Eric R. Teoh, *Roof strength and injury risk in rollover crashes of passenger cars and SUVs*, Presentation at the SAE Government/Industry Meeting, Washington, D.C.: Feb. 5, 2009. Jeremy Korzeniewski, "IIHS to Raise the Roof on Crush Standards," *Detroit News*, Feb 6, 2009.

The Santos/State Farm Test Program

Under a research grant from the Santos Family Foundation and using contemporary vehicles provided by the State Farm Mutual Auto Insurance Company, the Center for Auto Safety selected five of the 4 door sedans and five light trucks that NHTSA statically tested for Jordan Rollover System (JRS) dynamic testing of rollover occupant protection performance. The vehicles had all sustained damage (typically at the front) sufficient that they were deemed uneconomical to repair, but none of the damage affected the occupant compartment or roof. The sedans were a 2007 Pontiac G6, a 2006 Chrysler 300, a 2006 Hyundai Sonata, a 2007 Toyota Camry, and a 2007 Volkswagen Jetta. The light trucks were a 2007 Chevrolet Tahoe, a 2007 Jeep Grand Cherokee, a 2006 Honda Ridgeline 4-door pickup, a 2007 Honda CR-V, and a 2005 Volvo XC90. These vehicles all continue to be sold as 2008 models. Most, if not all, are being sold as 2009 models. We used extensive instrumentation and instrumented Hybrid III dummies restrained by three-point safety belts in the tests.

It is well known that the initially trailing side is the most vulnerable seating position for a belted occupant in a rollover. The critical aspects of rollover occupant protection are a strong roof, safety belts that fully restrain occupants in a rollover, interior padding in the head impact areas, and occupant compartment integrity to reduce partial or complete ejection. All of these vehicles had the padding in the upper interior as required by FMVSS 201. Although some of the light trucks had window curtain air bags, none were triggered in these tests.

The issue of whether a stronger roof will reduce injuries in rollovers has been settled in studies by NHTSA[3] and IIHS.[4] The latter showed that for mid-sized SUVs, an increase of roof strength (SWR) from 2 to 3 would reduce the injury rate by 25 percent (the current minimum FMVSS 216 requirement is a SWR of 1.5 and the proposed amendment would set the required minimum SWR at 2.5). The IIHS study of small passenger car rollovers found a similar, but somewhat smaller reduction in injury levels. This injury reduction is an order of magnitude higher than the prediction by NHTSA.

A few manufacturers including Volvo, Volkswagen and Toyota have voluntarily exceeded the minimum Federal requirements in some of their vehicles by substantial margins. Nevertheless, we have thus far seen only two production vehicles that provide good rollover occupant protection: the Volvo XC90 and the Volkswagen Jetta. The Honda CR-V showed fairly good rollover occupant protection performance despite its modest FMVSS 216 SWR. In designing the XC90, Volvo prepared a briefing discussing its dynamic tests to achieve the desired performance. A critical finding of the Volvo engineers is that the roof should not sustain permanent buckling or other structural failures.

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[3] Strashny, Alexander, *The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face during FMVSS 216 Rollovers*, National Highway Traffic Safety Adminstration, Washington, D.C.: 2008.

[4] Brumbelow, et. al., *ibid*.

Many manufacturers have substantially strengthened the B pillars and posts (where the rear of the front doors latch) and added a strong cross member between the B pillars to improve dynamic side impact performance under FMVSS 214 and the New Car Assessment Program (NCAP). This has also improved roof crush resistance in FMVSS 216, but not roof strength over the A pillars (the supports on either side of the windshield) or windshield headers as this is not independently tested in the current FMVSS 216 protocol (see Appendix A). In actual rollovers, most roofs are subjected to the primary impact force in the A pillar area because vehicles typically pitch forward as they roll. In the present test program, the first roll was conducted at a 5º pitch angle and the second at a 10º pitch to provide a range of roof impact test conditions that is typical of actual rollovers. FMVSS 216 tests only at 5º pitch.

Jordan Rollover System Tests

Test Procedure. The JRS suspends vehicles on mounts at the front and rear in a manner that permits them to roll freely. The mounts are released so that the vehicle falls as it is rotated and a road segment passes underneath. The initial roof contact with the moving road segment is on the passenger side (the initially leading or near side). This is followed by contact with the driver's side (initially trailing or far side) of the roof after which the vehicle is caught so that it will sustain no further damage. Two JRS tests were conducted of each vehicle: at a pitch angle of 5º for the first roll and 10º for the second. The road speed was 15 mph and the vehicles were dropped four inches to the first roof impact at a roll angle of 145º. The roll rate was 200º/second at the time of first roof impact.[5] These test conditions were derived from studies of actual rollovers and other dynamic rollover tests to emulate the conditions of actual rollovers.

Four string potentiometers were placed between the longitudinal roll axis of the vehicle and the roof structure at the top of the driver's side A-pillar and B-pillar, at the header inboard of the A-pillar and at the top of the passenger's side A-pillar. These instruments measure the amount and speed of roof intrusion to determine whether it was likely to injure a human whose head is in the path of the intruding roof.

An instrumented, safety belted 50th percentile male Hybrid III test dummy was placed in the driver's seat (the initially trailing side in this test). For the first roll, the dummy was seated generally as specified in FMVSS 208 for frontal crash tests except that the right shoulder joint was tightened and the dummies' hands were tethered together to prevent interference with the string potentiometers and damage to the dummy's arms from partial ejection. The dummy was instrumented with upper and lower six-axis (three force and three moment measures) neck load cells and string potentiometers were placed between the dummy and the seat. For the second roll, the dummy's torso was pitched to increase the angle of the neck axis to 10º forward, and the seat was moved rearward to place it in a more realistic position for a rollover condition. These changes were made

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[5] The test parameters are nominal target values. Actual parameters were within a few percent of these values.

when permitted by the condition of the vehicle. For some of the vehicles, the roof crush to the extent that the dummy could not be placed as planned. Seat belt load cells were used to measure belt tension in both tests.

Six vertical and two lateral load cells were placed in the moving roadway to record the impact characteristics of the test. A string potentiometer was placed on the front fixture support tower and another on the rear tower to record vehicle vertical motion characteristics during the test. A roll encoder was placed on the cable pulley which pulls the moving roadway to record the roadway velocity throughout the test. Another roll encoder was placed on the shaft of the vehicle roll axis or in the vehicle itself to record the vehicle roll angle and angular velocity during the test.

Rollover Occupant Protection Performance

Table 1 provides the basic results of these tests as they relate to the potential for injury for the five vehicles tested. The measurements that were used to evaluate performance included peak dynamic roof crush, peak crush intrusion speed, and residual roof crush.

Light Truck Year, Make & Model (strength-to-weight ratio – test weight)	Roll No.	Peak Roof Road Load (pounds)	Peak Dynamic Crush (inches)	Peak Crush Speed (mph)	Residual Roof Crush (inches)	Peak Axial Neck Load (N)	Neck Injury Criteria (upper)
2005 Volvo XC90 (4.6 - 4,450 pounds)	1	19,521	1.7	1.9	0.5	2,889	0.52
	2	22,145	3.6	2.6	1.9	3,628	1.05
2007 Honda CR-V (2.6 - 3,389 pounds)	1	16,115	3.4	4.0	1.8	5,583	1.02
	2	14,264	6.5	5.4	3.6	3,687	1.30
2007 Chevrolet Tahoe (2.1 - 5,475 pounds)	1	24,727	7.9	6.1	5.8	6,101	1.09
	2	16,732	14.0	11.6	10.9	3,318	0.81
2007 Jeep Grand Cherokee (2.2 - 4,692 pounds)	1	17,037	8.4	7.9	6.5	9,757	1.75
	2	11,256	11.8	9.3	9.1	6,781	2.07
2006 Honda Ridgeline (2.4 - 4,499 pounds)	1	20,385	9.4	13.7	6.3	10,006	1.64
	2	9,182	16.5	15.0	13.2	4,685	1.19

Note 1: The Volvo XC90 SWR was probably higher than 4.6. The test was stopped after the equipment reached the limit of its ability to apply force to the roof.

Note 2: We also measured the Integrated Bending Moment (IBM), a newly proposed measure of the dummy neck, in all of these tests. The results for the first and second tests were: Tahoe – 18.9 and 21.8, Jeep – 29.4 and 20.2, Ridgeline – 24.1 and 28.9, CR-V – 8.5 and 18.7, and XC90 – 2.0 and 11.3. It has been suggested that an IBM value above 15 indicates a high potential for a neck injury.

Table 1 – Light Truck JRS Test Results

NHTSA has concluded that if the residual roof crush (the distortion of the roof after the test is completed) leaves negative headroom for a 50th percentile male, the probability of occupant head, face or neck injury increases dramatically. As can be seen from Table 1, the peak dynamic intrusion (the maximum crush during the test) is typically 50 to 100 percent greater than the residual intrusion. Only one of the tested light trucks, the XC90, had peak intrusion within the NHTSA's safe value; and only two had residual roof intrusion that would not have contacted a normally seated dummy occupant's head.

There are several ways of measuring the potential for neck injury from roof intrusion. Peak Axial Neck Load measures the direct neck compression along the vertical axis. The Neck Injury Criterion is NHTSA's combined measure of neck compression and forward bending moment. Based on both experimental tests and real world crash statistics, NHTSA has established that if the neck injury criterion, N_{ij} exceeds 1, there is a 15 percent probability that the occupant will suffer an AIS 3 or greater neck injury. The Integrated Bending Moment is a newly proposed measure that is the vector sum of the measured lower neck moments M_x and M_y, integrated over the time duration of neck loading.

The ratio of the peak road load in the first roll to the peak in the second roll decreases with increasing SWR indicating that the vehicles with stronger roofs respond more similarly in multiple rolls than vehicles with weak roofs.[6] Belt loads were nominal (no more than a few hundred pounds) in all tests.

We looked in detail at the roof to road load in these tests, and the results are shown in Appendix A. These loads show a roof's dynamic crush resistance. A large disparity between the loads in the first and second roll is an indication that the roof was seriously weakened in the first roll.

Details of Vehicle Performance

2005 Volvo XC90. The XC90, which weighs 4,450 pounds, was one of the best performing vehicles we have tested on the Jordan Rollover System. This is the third XC90 that has been tested on this machine, and all have shown good rollover occupant protection performance. Even the side windows survived both JRS tests in this series.

The XC90 suffered a modest outward buckle of the windshield header after the second test, but little roof intrusion on either test as shown in Figure 6. The roof intrusion rates and peak dummy neck loads were low and easily survivable. In these respects, the XC90 which had an FMVSS 216 SWR of at least 4.6[7] was the best performer of the ten vehicles included in this test including the Volkswagen Jetta which, at 5.1, had the highest SWR of the vehicles NHTSA tested in 2008.

The contrast between the Volvo and the Honda Ridgeline, two similar size and type vehicles designed around the same time, is stark and dramatic. It would be difficult to suffer a serious injury in an uncomplicated rollover in the former, and difficult to avoid such an injury if seated in the front trailing side seat in the latter.

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[6] In vehicles with weak roofs, the peak force on the road on the second side impact occurs when the roof has crushed and the lower body of the vehicle comes in contact with the road segment.

[7] The test on this vehicle was halted when the force applied to the roof reached the limit of the machine.

Figure 6. After the first test (left), the roof of the 2005 Volvo XC90 showed virtually no damage. After the second roll (right), damage was modest.

2007 Honda CR-V. The CR-V's curb weight is 3,389 pounds. Figure 5 shows the 2007 Honda CR-V after the first and second rolls. It registered a maximum road impact load with the first side of the roof of 15,032 pounds and of 16,115 pounds on the second side on the first roll test.

The FMVSS 216 SWR was 2.6 on the first side and 2.5 on the second. The fact that the strength on both sides was nearly equal indicates that Honda was not relying excessively on the windshield for its FMVSS 216 performance. These numbers are equal to NHTSA's proposed FMVSS 216 roof strength upgrade, but have no performance margin should such a standard be adopted.

Despite the rather modest SWR measurements, which were little different than any of the other light trucks except the Volvo XC90, the CR-V performed significantly better in the JRS test than the Tahoe or Grand Cherokee. It performed substantially better than the Honda Ridgeline which is designed and manufactured by the same company, and has nearly the same FMVSS 216 SWR.

Figure 5. 2007 Honda CR-V after the first roll (left) and second roll. The vehicle's front end damage occurred before the test and did not affect the occupant compartment or roof integrity.

The damage to the initially trailing side of the roof was modest on the first roll and increased only moderately in the second roll. The side windows survived the first roll, but the driver's window broke in the second roll.

2007 Chevrolet Tahoe. The Tahoe's curb weight is 5,475 pounds. Its gross vehicle weight rating exceeds the limit in FMVSS 216, so it is not covered by that standard. It would be covered in the proposed amendment to that standard. Figure 1 shows the 2007 Chevrolet Tahoe after the first and second rolls.

General Motors has indicated that is makes extensive use of high strength steels in the roof of the sister 2007 Cadillac Escalade. We assume that the Tahoe's roof structure has the same roof design and material since they share the same platform. Either high strength steel was used primarily to reduce vehicle weight or this material was used only in the Escalade. This vehicle also shares a platform with the GMC Yukon.

The roof of this vehicle showed weak FMVSS 216 performance and poor JRS performance. Its JRS performance was similar to the Jeep Grand Cherokee except that it did not develop the major windshield header and roof panel buckle as did the Jeep. The Tahoe has an FMVSS 216 SWR of 2.1, the lowest among all the tested passenger cars and light trucks. In NHTSA's two-sided test, it registered a SWR of only 1.7 on the second side before crushing to 5 inches or to contact the occupant's head. It would not have met the agency's proposed upgrade of FMVSS 216.

The Tahoe registered a maximum road impact load with the first side of the roof of 17,664 pounds, and of 24,727 pounds on the second side on the first roll test. The near side could resist with only 9,295 pounds showing serious weakening of the structure. A higher road impact load of 39,575 at the end of the second test occurred after the roof impact because of the impact between the lower body of the vehicle and the road. The total residual roof intrusion at the A pillar was 5.8 inches after the first roll and 10.9 inches after the second.

The far side of the roof of the Tahoe suffered substantial crush and the windshield header buckled outward in the first roll. The second roll resulted in further buckling of the windshield header and more substantial inward and downward movement of the A and B pillars. Both the driver's side door windows broke in the first roll.

Figure 1. 2007 Chevrolet Tahoe after first (left) and second roll JRS tests. Note that damage to the front of the vehicle occurred before the JRS tests, but did not affect the performance of the occupant compartment structure or roof in these tests.

The roof intrusion rate on the second roll would have inflicted serious injury to a driver whose head is located in the path of maximum intrusion. Overall, this vehicle would be considered poor because of the high neck loads on the first roll and its excessive roof intrusion and intrusion speed on the second roll.

2007 Jeep Grand Cherokee. The Jeep's curb weight is 4,692 pounds. Figure 2 shows the 2007 Jeep Grand Cherokee after the first and second rolls. It registered a maximum roof road impact load with the first side of the roof of 11,107 pounds and of 17,037 pounds on the second side on the first roll test. The vehicle continued to fall after the far side roof impact and the side of the vehicle registered an impact force of 23,908 pounds.

The FMVSS 216 SWR was 2.2. In NHTSA's two sided test, the Grand Cherokee had a SWR of only 1.6 on the second side before there was either head contact or 5 inches of roof intrusion. This shows the degree to which Chrysler relies on the vehicle's windshield to comply with this standard. The Jeep Grand Cherokee would not meet the roof crush resistance value proposed by NHTSA in 2005.

The major damage and intrusion of the roof panel over the driver position occurred on the first roll and was only moderately increased on the second. The total residual roof intrusion at the A pillar was 6.5 inches after the first roll and 9.1 inches after the second. However, the roof developed a substantial inward buckle in the windshield header and roof panel over the driver position, and the dummy injury measures were higher than in the Chevrolet Tahoe as a consequence (see Figures 3 and 4).

Figure 2. 2007 Jeep Grand Cherokee after the first (left) and second (right) roll on the JRS.

The Jeep's roof showed serious weakness in our dynamic testing. We would rate the rollover occupant protection capability of this vehicle as unacceptable based on the amount and speed of roof intrusion at the buckle that formed over the driver position, and on the high peak neck load and neck injury criterion in these tests. The driver's side window broke on the first roll, and the left rear door glass broke on the second.

Figure 3. Views of the windshield header and roof panel buckle after the first roll (left) and second (center and right). The right picture shows the extent of interior intrusion.

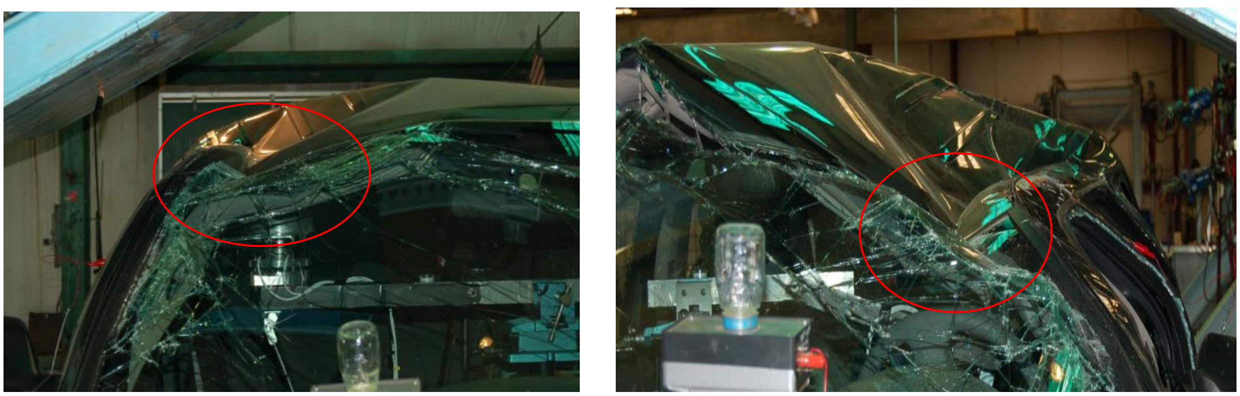

Figure 4. View of the Jeep Grand Cherokee after the right side NHTSA FMVSS 216 test (left) and second (drivers) side test. Note that the roof buckled at the same point as in the JRS test, but that the buckle was not as severe

2006 Honda Ridgeline. The Honda Ridgeline 4-door pickup is unique. It is built on a unit body platform that it apparently shares with the Honda Pilot, and is available only in this body size and style. It weighs 4,499 pounds. The initially leading side of the roof sustained a force of 13,544 pounds and the trailing side sustained a force of 20,385 pounds.

The Ridgeline achieved a SWR of 2.4 in the FMVSS 216 test, but was also unique in demonstrating by far the poorest performance of any of the ten vehicles included in this passenger car and light truck test series (Figure 5).

On the first roll, the roof developed a significant buckle in the windshield header and had a roof intrusion speed that would have severely injured an occupant in its path. On the first roll, the dummy registered the highest neck load of any vehicle in this test series. On the second roll, the near side of the roof could muster only the dummy's head was caught under the roof rail in a manner that severely wrenched its neck, rotating the dummy's head nearly 90º to the left. Although there is no measure for injury from this situation, it is almost certain that a human in this situation would have been severely injured.

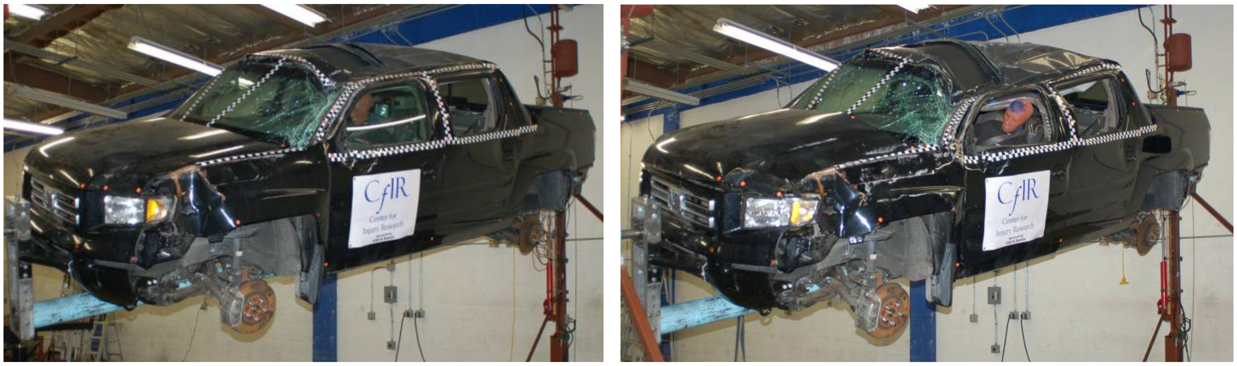

Figure 5. The 2006 Honda Ridgeline after the first JRS test (left) and the second (right).

We found this vehicle to be seriously defective in its rollover occupant protection performance because of the catastrophic, rapid collapse of the roof and its massive intrusion into the occupant survival space. We recommend that NHTSA conduct a safety defect investigation of its rollover occupant protection capability. The Honda Pilot should be included in any such investigation to the extent that its design is similar to that of the Ridgeline.

Discussion

Roof Strength. Occupant compartment integrity (resistance to intrusion and occupant containment) was recognized by Hugh DeHaven as a critical factor in motor vehicle crash safety in 1952.[8] In recognition of DeHaven's insight, NHTSA specifically identified occupant ejection and roof crush as the critical factors in rollover safety in the late 1960s. In 1970, the agency proposed two standards to deal with these challenges: the dolly rollover test of FMVSS 208 to deal with ejection and the roof crush resistance standard, FMVSS 216.[9]

In its originally proposed form, a two-sided roof crush test conducted at a pitch angle of 10º to appropriately stress the A pillar, FMVSS 216 would have had a major positive impact on rollover safety. Earlier tests by C*f*IR have demonstrated that vehicles with a given SWR in the FMVSS 216 test could achieve an SWR of only about half that value on the second side when the test is conducted at 10º pitch, as NHTSA originally proposed. Thus, vehicles that could achieve a SWR of 1.5 to 2 on the original test could probably achieve an SWR of 3 to 4 on the present FMVSS 216 test. However, even had this more rigorous test been adopted in the early 1970s, it should have been replaced by a dynamic test by 1977 as NHTSA said it would do in December 1971 when it issued the FMVSS 216 that remains essentially unchanged to this day. [10]

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[8] DeHaven, Hugh, "Accident Survival – Airplane and Passenger Automobile," Paper Presented at the Annual Meeting of the Society of Automotive Engineers, January 1952, *reprinted in* William Haddon, Jr., MD, W.A. Suchman, D. Kline, *Accident Research Methods and Approaches,* Harper & Row, New York: 1964.

[9] NPRM, 35 FR 7187 (May 7, 1970); NPRM, 36 FR 166 (Jan. 6, 1971).

[10] DOT Press Release, NHTSA 109-71 (Dec. 11, 1971). See attached copy.

Recent research by the Insurance Institute for Highway Safety (IIHS) has demonstrated that an increase of one unit in SWR results in an overall reduction of roughly a quarter in rollover injury rates of all types. We would conclude from this result that had the originally proposed FMVSS 216 taken effect, the savings would have been around 3,000 lives per year in rollovers. However, the time is long past that an upgrade in the requirements of FMVSS 216 would be sufficient: there is too much evidence that the FMVSS 216 test does not effectively measure a vehicle's ability to provide good rollover occupant protection. The present tests show that only a well-designed dynamic performance test; such as the JRS; can adequately, objectively, and practicably meet the need for motor vehicle safety.

Improvements in occupant compartment structure have been made by most automakers, but the impetus for such improvement seems to be a desire to improve vehicle performance in the various dynamic frontal and side impact tests from the New Car Assessment Program and the Insurance Institute for Highway Safety. For example, the Subaru Forester that was used in the JRS repeatability had a very strong B pillar/roof bow structure that was apparently designed to improve side impact performance. Toyotas have shown good compression strength in their A pillar/roof rail structures, apparently to give a good upper load path for offset frontal collision tests. While these features improve FMVSS 216 test performance, the JRS tests show that these vehicles' roofs have inadequate lateral shear resistance at the A pillar and poor windshield header strength. For these vehicles, attention to the A pillar/windshield header/front roof rail area would dramatically improve rollover occupant protection performance at very little cost.

Roof Strength and Ejection. Roof strength is critical not only to reduce roof intrusion that can directly injure an occupant. It provides a secondary benefit in reducing the potential for side window breakage that can facilitate partial and complete ejection. Even occupant ejection protection features such advanced glazing systems and window curtain air bags cannot provide fully effective protection is there is substantial roof crush in a rollover.

This has been demonstrated by the reduction in glazing failures in the present tests where there was only modest roof crush over the side windows. It was also found to be true in the General Motors Malibu tests conducted in the 1980s where significantly fewer side windows failed in the vehicles with roll cages in dolly rollover tests. Crash investigations also demonstrate that even tempered glass side window glazing can survive a rollover if the roof above them is not seriously distorted.

Quasi-Static versus Dynamic Testing. Despite the IIHS findings of a correlation between SWR and occupant injury in rollovers, we have found that quasi-static tests such as FMVSS 216 cannot provide an efficient or practicable measure of rollover occupant protection. If manufacturers are encouraged to design vehicles to achieve high SWR ratings in FMVSS 216 tests, they will design vehicles that perform well in these tests, but those vehicles may not provide optimal occupant protection in actual rollovers.

This test series has not only shown the wide range of rollover occupant protection performance available in today's automotive products, it shows that the correlation between FMVSS 216 SWR test results and more realistic dynamic test performance is poor. The best and worst performers in our tests did not have the highest or lowest FMVSS 216 test scores.

The reasons for the lack of correlation are several-fold:

- The dynamic responses of complex steel roof structures are different from their quasi-static response. The response of most vehicles to the FMVSS 216 test is for the roof to flatten against the platen so that when it is removed, the roof mirrors the flat shape and angle of the platen. In dynamic tests, weaker roofs show buckles and other irregular distortions, particularly in the windshield headers that are similar to the damage induced by actual rollovers. Such structural failures tend not occur in FMVSS 216 tests.

- The quasi-static tests cannot measure the effect of geometric shape. A square vehicle shape, such as the Honda Ridgeline, will sustain much higher forces when the corners of the roof encounter the roadway than a rounded shape such as the Volvo XC90. The latter rolls like a barrel while the former rolls like a box.

- The quasi-static tests at 5º pitch permit designs that share loads between the A and B pillars and that do not apply strong shear loads across the roof. Manufacturers have been selectively strengthening parts of roof structures: A pillars and roof rails to improve longitudinal load paths for offset frontal crashes, and B pillars and roof bows to improve side impact protection performance in dynamic side impact tests. They have generally ignored windshield header strength and roof shear strength so that the most common failure observed in dynamic rollover tests (as well as in actual crashes) is buckling of the windshield headers. Manufacturers also routinely measure peak SWR of a roof before there is significant loss of the contribution of the windshield to overall roof shear strength. Windshields virtually always fail early in a rollover, so that their contribution to roof crush resistance is lost.

- A quasi-static test cannot measure the speed of roof intrusion which is a critical factor in head and neck injury. The intrusion speed on the first roll of the four light trucks with similar SWRs (ranging from 2.1 to 2.6) in this test series ranged from 4 to over 13 mph. The intrusion speed of a buckle is often much higher than the vehicle's drop speed.

- The quasi-static test does not show differences in protection given side glazing that are apparent in the dynamic tests. For example, a vehicle with a SWR of 2.5, the Chrysler 300, had no side window breakage in either test while the Hyundai Sonata with a SWR of 3.2 lost its driver's side window in the second test. This will become more important if manufacturers are required to meet more rigorous ejection protection requirements in the future.

- A strong roof affects the rollover dynamics in a subtle way. If the initial impact of the leading side of the roof stops the fall of the vehicle's center of gravity, the second side impact is less severe because the second side does not have to lift the vehicle. The video of the present tests show this effect. When the first side of a vehicle with a weak roof hits the road surface, it only modestly crushes, but the vehicle continues to fall and roll onto the flat of the roof. Then the far side of the roof must not only stop the fall of the vehicle, it must lift it or it will crush – as did the Tahoe and Grand Cherokee roofs – in the attempt to do so.
- Vehicle performance under multiple rollovers cannot be assessed using a quasi-static test. A key factor is the degree of elasticity in the roof structure. A roof with a high degree of elasticity will retain much of its strength after a first roll, leaving it capable of offering protection in a second or third roll. This effect is clearly shown in the roof to road load data discussed in Appendix A

Conclusions

The present tests show the very wide range of rollover occupant protection performance of light trucks currently on the market. They also demonstrate that a dynamic test can show dramatic differences in rollover occupant protection performance of vehicles with similar FMVSS 216 strength to weight ratios. The Honda CR-V, which had a SWR little more than half that of the Volvo XC90, had performance that was nearly as good as the Volvo. By comparison, the Honda Ridgeline with nearly the same SWR as the CR-V had miserable performance in the JRS tests.

The problem with FMVSS 216 is that it gives a vehicle designer the wrong target for rollover occupant protection. The fact that two Honda models can have such radically different performance in our more realistic dynamic tests shows the inadequacy of the FMVSS 216 quasi-static test. The discussion of problems with the rollover performance of contemporary Toyota cars and light trucks in Appendix C of our paper on the Santos/C*f*AS tests of passenger cars also illustrates this point.

One of the most consistent weaknesses that these tests illustrated – in both passenger cars and light trucks – is weakness in windshield headers. All of the tested vehicles had buckles develop in the windshield headers, with the worst being the Jeep Grand Cherokee, the Honda Ridgeline, the Pontiac G6 sedan, and the Hyundai Sonata. The Volvo XC90 had only minor outward buckling, and several others had buckling that did not significantly intrude into the occupant compartment. However, all vehicles showed at least some compromise of roof strength in the second roll as a consequence of windshield header damage. The FMVSS 216 quasi-static test shows the tendency toward windshield header buckling of the type illustrated by the JRS tests (and in actual rollovers) only with particularly weak roofs such as the Grand Cherokee. We recommend that automotive designers need to give particular attention to windshield header design to improve rollover roof performance.

A dynamic test such as the JRS would be little more expensive to perform than the quasi-static test of FMVSS 216. Designing to a dynamic test can be conducted using finite element analysis and good engineering practice. The development of a new vehicle to comply with the dynamic test would be little different than the development of current vehicles, and the extra cost to comply with a dynamic test would be trivial in comparison with the cost of common safety options on new vehicles including window curtain air bags and electronic stability systems. By contrast, the benefits of substantially improve rollover occupant protection would be major: tens of billions of dollars per year, not to mention the major reduction in pain and suffering from rollover casualties.

We believe that the Santos/C*f*AS tests have provided a major advancement in the field of rollover occupant protection at a remarkably modest cost. The tests provide a basis for the development of a genuinely improved FMVSS 216 and/or a New Car Assessment Program rating of rollover occupant protection.

Appendix A. Roof Forces in Rollovers

One major advantage of JRS testing is that the force between the vehicle and the road is continuously measured as a function of time and roll angle. These road load forces are a good indication of the strength that must be built into the roof to provide good rollover performance. An important finding from this data is that differences in performance between the first and second rolls indicate the degree to which the strength of the roof has been compromised by the impacts of the first roll.

JRS tests shows that a vehicle roof must be capable of sustaining at least four times its weight when that force is applied dynamically,[11] and its structural components must not sustain major plastic damage so that it is capable of sustaining a second roof impact. For weak roofs the near side of the roof does not adequately slow the vehicle's fall, imposing an even greater demand on the far side. If the roof cannot support the vehicle through the rollover; and as the far side of the roof crushes, the vehicle continues to fall as it rolls. As a consequence, the upper side of the vehicle's lower body strikes the road. This impact typically raises the vehicle rapidly as can be seen in video of the tests.

Both the light trucks and the passenger cars showed a substantial range of road load performance. We propose that from these tests, the ratio of the road load during the near side impact on the second roll to the vehicle's weight is a simple indicator of dynamic roof crush performance and the preservation of its strength following whatever damage occurs in the first roll. Let us call this number RL2N.

Light Truck Performance

Volvo XC90. For the Volvo XC90, which has a strong roof, the road load force is completely due to contact between the vehicle roof and the road surface. Figures A1 and A2 show the road load force of the Volvo XC90 during its first and second rolls. These traces of the total vertical roof force show clear peaks when the first and second sides of the roof strike the road. In the first roll, the near side force was 19,521 pounds (4.4 times the weight of the vehicle) and the far side roof force was 18,229 pounds. In the second roll, the force on the first side was 16,130 pounds and the second was 22,145 pounds, showing that the damage from the first roll weakened the roof to some degree. Nevertheless, the elastic response of the roof in the first roll helps to keep the roof reasonably strong for the impacts in the second roll. The RL2N for this vehicle is 3.6.

Honda CR-V. Figures A3 and A4 show that the CR-V performed nearly as well as the Volvo. However, in the second roll, there is a second peak on the far side impact. This is because the near side of the roof does not halt the vehicle's fall as well as in the first roll, and far side of the roof is not able to halt the vehicle's fall. The second peak on

[11] It should be noted that steel is a rate sensitive material, and that it can sustain roughly 20 percent more force when it is applied dynamically than when applied quasi-statically. However, because of the complexity of the structure of vehicle roofs, the relationship between quasi-static crush resistance and dynamic performance cannot be accurately predicted.

the far side is from the CR-V lower body's impact with the road surface. While this impact is not itself dangerous, it does indicate that the roof could not fully resist intrusion from the far side impact. The RL2N for the CR-V is a respectable 3.4.

Chevrolet Tahoe. This vehicle showed moderate roof load (17,664 pounds – just over three times the vehicle's weight) on the near side impact in the first roll, and 24,727 pounds initially on the far side impact of the roof, but then a second peak comes from the vehicle's lower body contact with the road (another 17,000 pounds). On the second roll, the near side could resist with only 9,295 pounds, and since the roof almost completely collapsed on the far side, the roof resisted with 16,732 pounds and the force on the side of the body rose to 39,575 pounds in order to halt the fall of the Tahoe. The RL2N for the Tahoe, 1.7, was the lowest of all vehicles tested although the Tahoe's roof did not buckle as severely as the Jeep or the Honda Ridgeline.

Jeep Grand Cherokee. The Jeep showed even less near side resistance on the first and second rolls than the Tahoe. The roof buckled on the first roll and collapsed and buckled inward quite dangerously on the second roll. Its RL2N was 2.1.

Honda Ridgeline. The worst performer overall showed modest roof crush resistance in the first roll, 13,544 pounds on the near side and 20,385 pounds on the far side, but that was not sufficient to stop the fall: the side of the vehicle produced a load of 14,000 pounds at the end of the roll. The second roll had much lower roof load: 9,182 pounds on the near side, and catastrophic collapse on the second. Its RL2N was 2.0.

Passenger Car Performance

Volkswagen Jetta. The Jetta was the best sedan tested. It looked much like the Volvo in its first roll, Figure A11, but not on its second. The roof had been significantly weakened on the first roll so that on the second roll, the near side road load was almost 40 percent lower and the side of the vehicle had to halt its fall. Although the Volkswagen could achieve a FMVSS 216 SWR of over 5, its structure apparently does not have the elastic response of the Volvo's roof. The weak member in this roof, as with many others, is the windshield header. The Jetta's RL2N was 3.0.

Toyota Camry. This vehicle gave a similar performance to the Volkswagen except that there was minor contact with the vehicle's side on the first roll and major contact on the second. While the Volkswagen's windshield header buckled upward at the center, the Camry's sustained a modestly intruding buckle over the driver position that was potentially more threatening to the driver. As with the Jetta, the weak point of this roof is its windshield header. The Camry's RL2N was only 2.2.

Hyundai Sonata. Figures A15 and A16 show that the Sonata was marginally worse than the Camry. Its near side road load going from 12,955 on the first roll to 9,389 pounds on the second roll. Its RL2N was 2.6.

Chrysler 300. The 300 (Figures A17 and A18) was marginally worse than the Hyundai, with the near side road load going from 11,604 pounds to 6,980 pounds on the first and second rolls. Its RL2N was 1.8.

Pontiac G6. The Pontiac brings up the bottom with a near side road load only 10,605 pounds on the first roll and 6,308 pounds on the second. In effect, the Pontiac looked as bad on its first roll as the Volkswagen did on its second roll. Its RL2N was 1.9.

The road load tells a lot, but not the whole story, about a vehicle's roof performance in a rollover. It shows not only the initial strength of the roof, but the degree to which the vehicle will continue to perform well after the roof damage in the first roll. It does not show what can easily be seen by inspecting the vehicles after the tests: whether the roof buckled or collapsed in a dangerous manner into the occupant survival space.

Tested Vehicle	First Roll (pounds)		Second Roll (pounds)		Near Side Ratio	RL2N
	near side	far side	near side	far side		
2005 Volvo XC90 4,450 lbs.	19,521 4.4	18,229 4.1	16,130 3.6	22,145 5.0	83%	3.6
2007 Honda CR-V 3,389 lbs.	15,032 4.4	16,115 4.8	11,128 3.3	14,264 4.2	74%	3.3
2007 Chevrolet Tahoe 5,475 lbs.	17,664 3.2	24,727* 4.5	9,295 1.7	16,732* 3.1	53%	1.7
2007 Jeep Grand Cherokee – 4,692 lbs.	11,107 2.4	17,037 3.6	10,024 2.1	11,256* 2.4	90%	2.1
2006 Honda Ridgeline 4,499 lbs.	13,544 3.0	20,385 4.5	9,182 2.0	8,046* 1.8	68%	2.0

Table 1. Road load in roof impacts. Numbers below road loads are the ratios of road loads to vehicle weight.

Tested Vehicle	First Roll (pounds)		Second Roll (pounds)		Near Side Ratio	RL2N
	near side	far side	near side	far side		
2007 Volkswagen Jetta 3,272 lbs.	16,501 5.0	17,362 5.3	10,312 3.2	13,550 4.0	62%	3.2
2007 Toyota Camry 3,260 lbs.	14,188 4.3	19,242 5.9	7,506 2.3	19,453 5.9	53%	2.3
2007 Hyundai Sonata 3,266 lbs.	12,955 4.0	17,410 5.4	9,389 2.9	8,939* 2.7	72%	2.9
2007 Chrysler 300 3,726 lbs.	11,604 3.1	21,110 5.6	6,980 1.9	6,354* 1.7	60%	1.9
2007 Pontiac G6 3,422 lbs.	10,605 3.1	16,035 4.7	6,308 1.8	8,409* 2.5	59%	1.8

Table 2. Road load in roof impacts of passenger cars. Numbers below road loads are the ratios of road loads to vehicle weight.

* Peak load from impact of the side of the vehicle, after the roof failed to halt its downward fall, was higher.

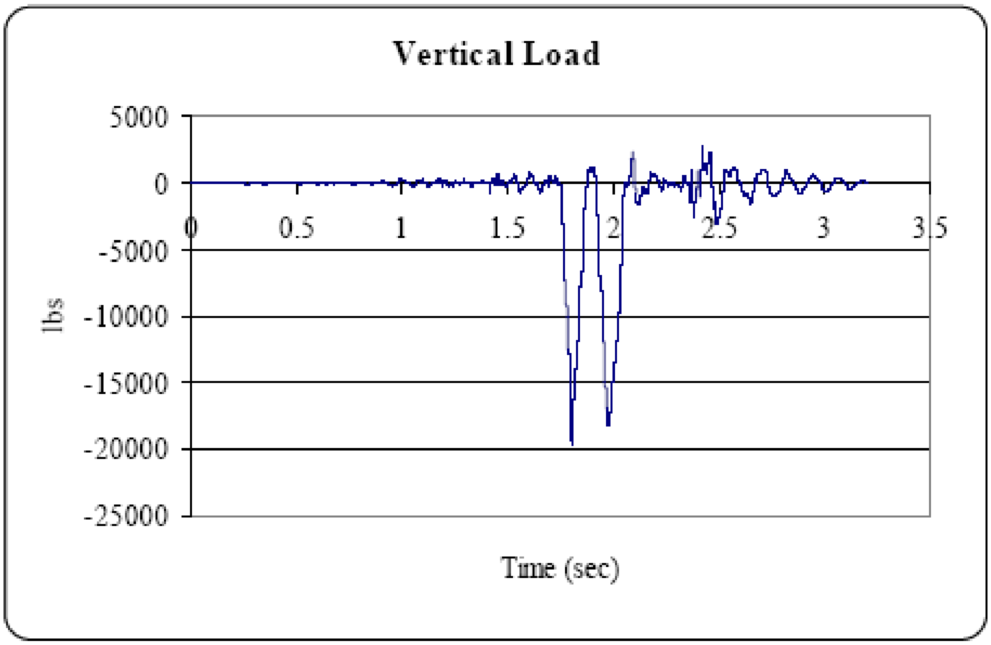

Figure A1. Volvo XC90 – Roll 1 – Total Vertical Load versus Time.

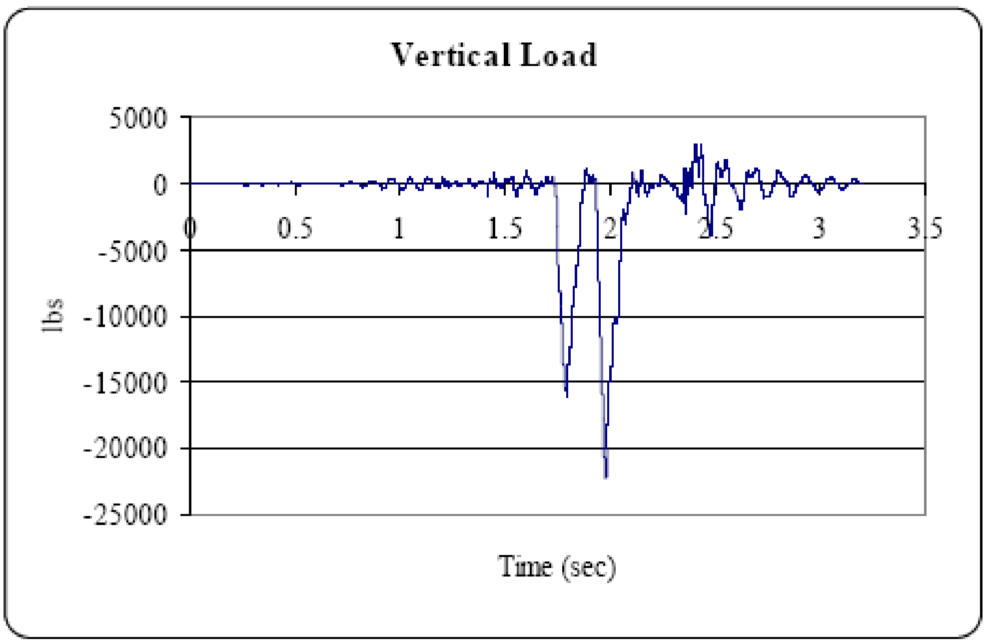

Figure A2. Volvo XC90 – Roll 2 – Total Vertical Load versus Time.

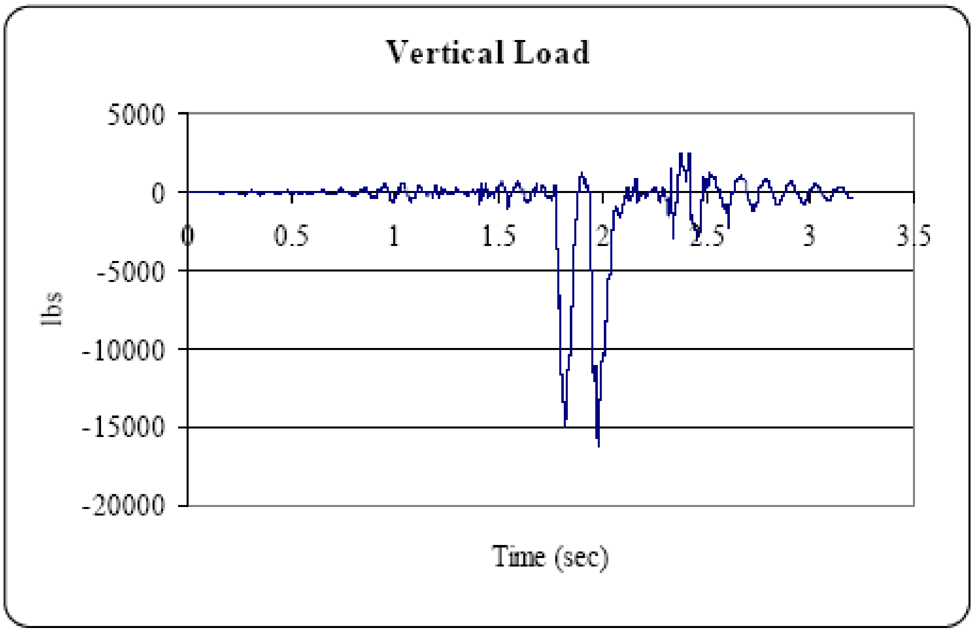

Figure A3. Honda CR-V – Roll 1 – Total Vertical Load versus Time.

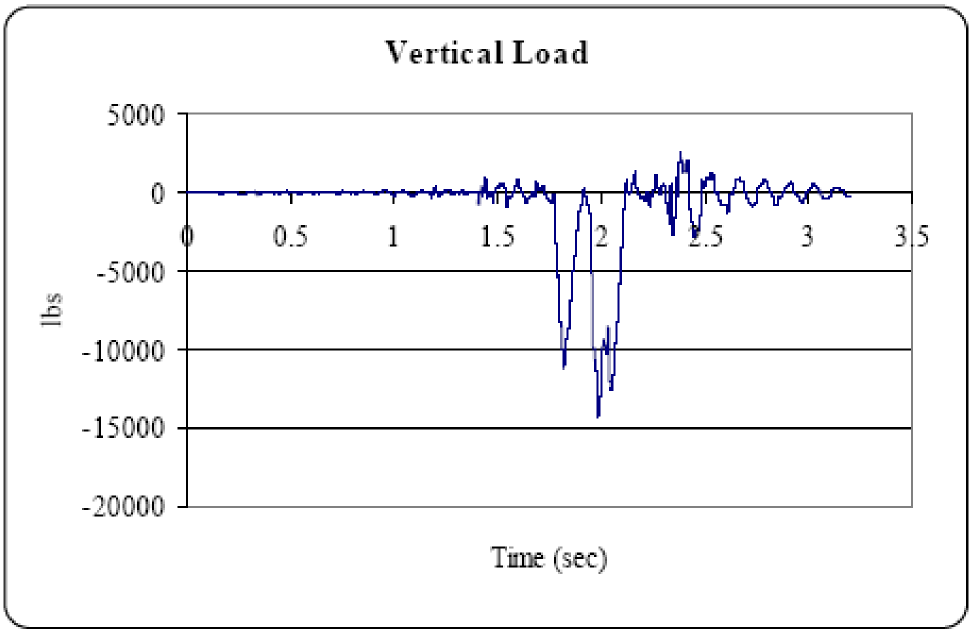

Figure A4. Honda CR-V – Roll 2 – Total Vertical Load versus Time.

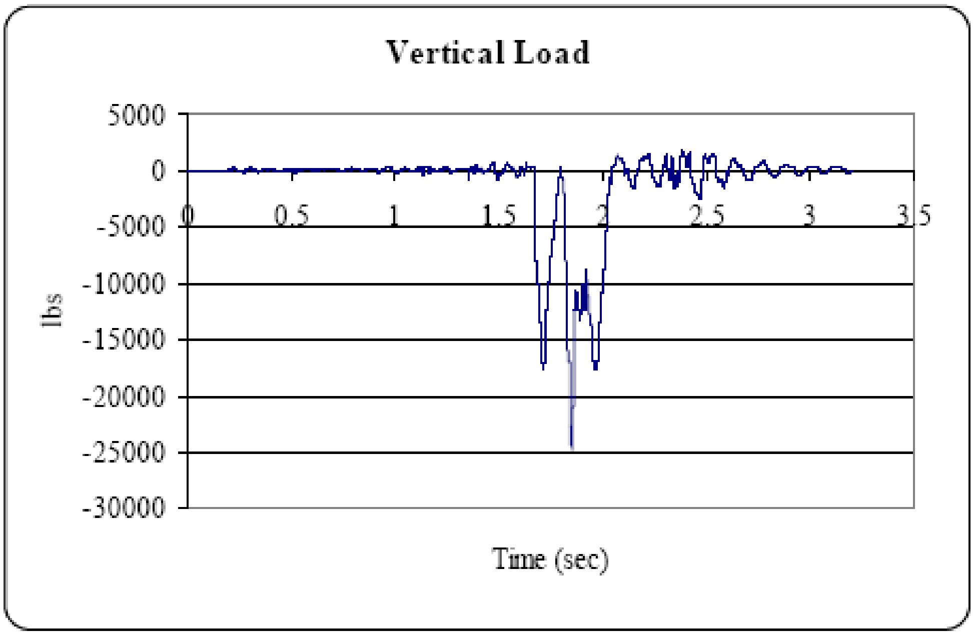

Figure A5. Chevrolet Tahoe – Roll 1 – Total Vertical Load versus Time.

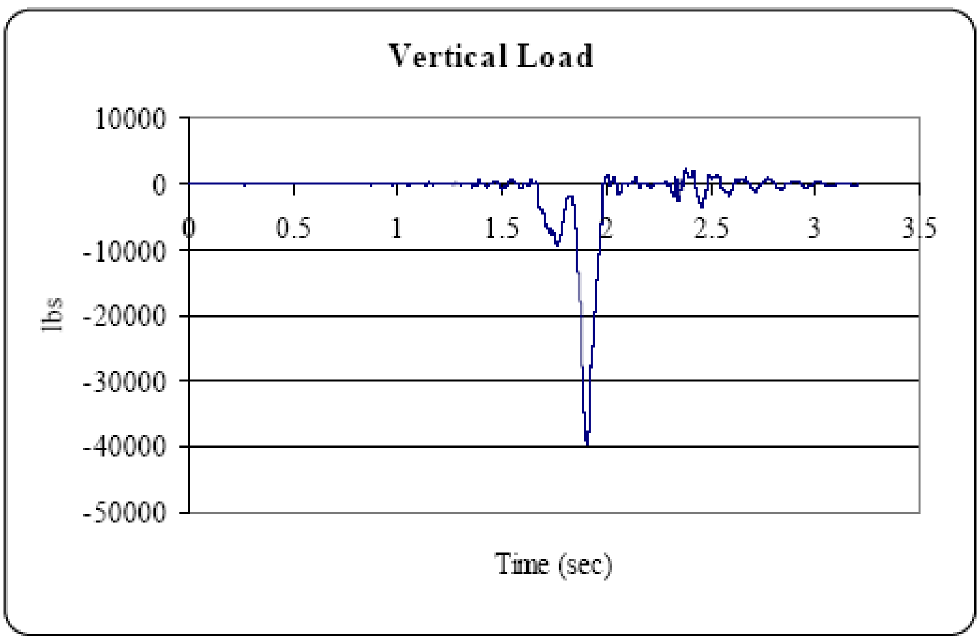

Figure A6. Chevrolet Tahoe – Roll 2 – Total Vertical Load versus Time.

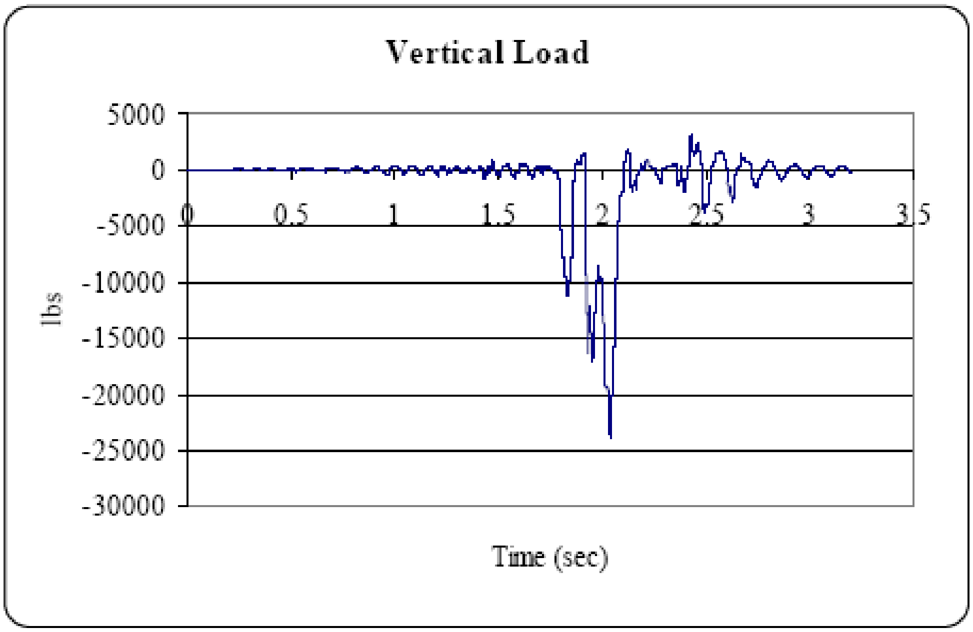

Figure A7. Jeep Grand Cherokee – Roll 1 – Total Vertical Load versus Time.

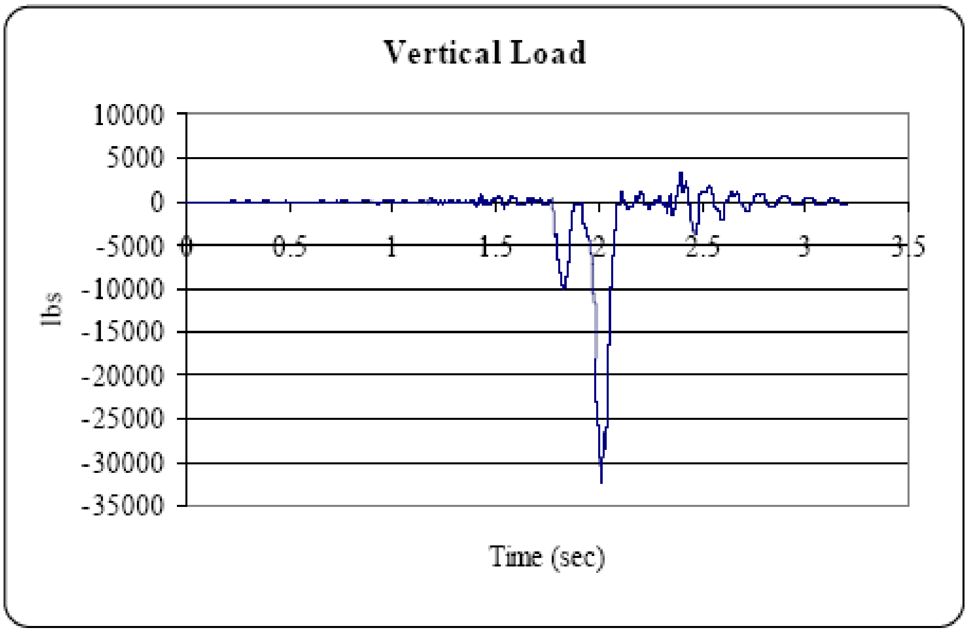

Figure A8. Jeep Grand Cherokee – Roll 2 – Total Vertical Load versus Time.

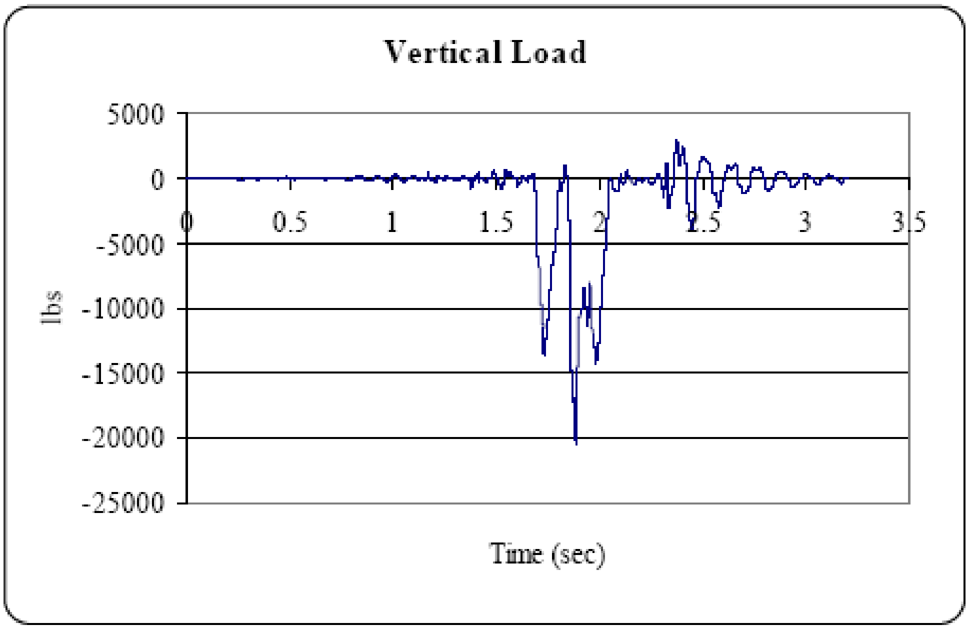

Figure A9. Honda Ridgeline – Roll 1 – Total Vertical Load versus Time.

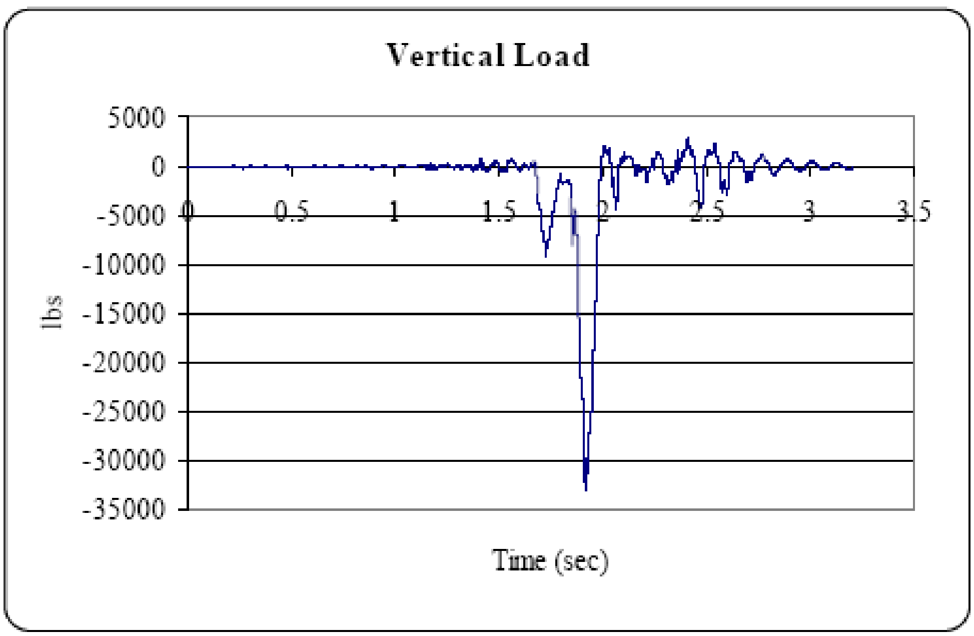

Figure A10. Honda Ridgeline – Roll 2 – Total Vertical Load versus Time.

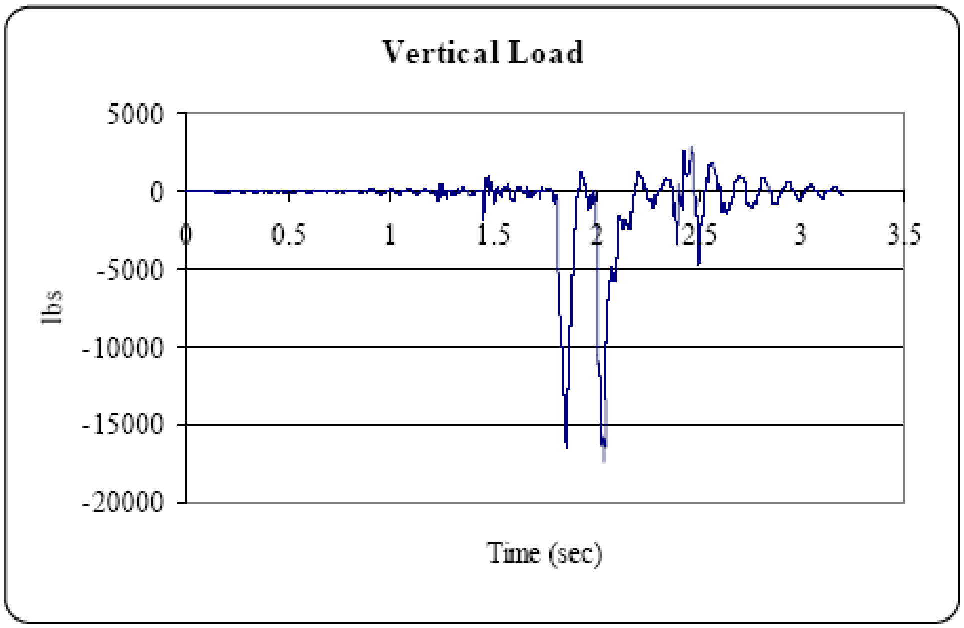

Figure A11. Volkswagen Jetta – Roll 1 – Total Vertical Load versus Time.

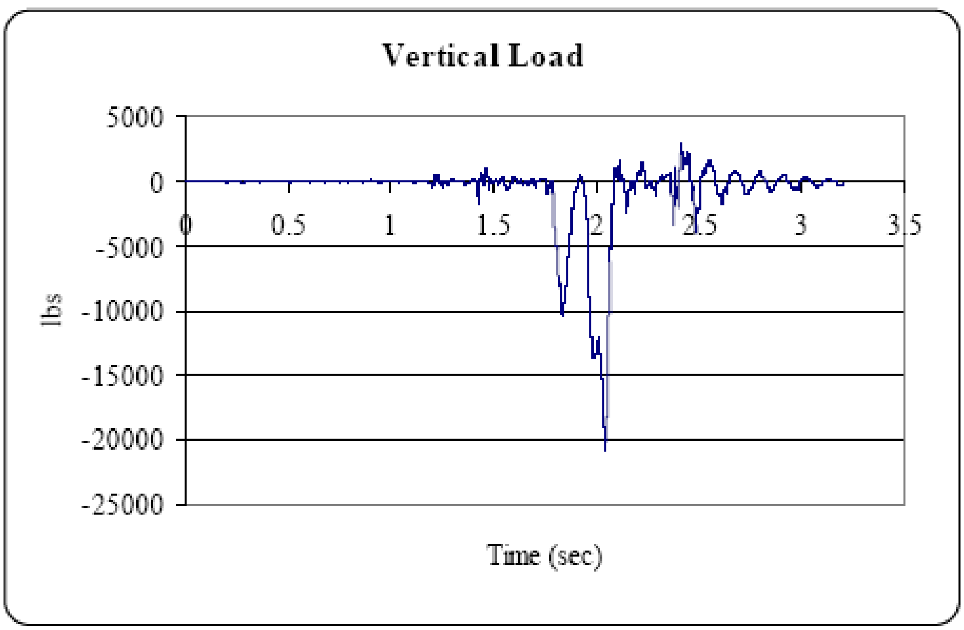

Figure A12. Volkswagen Jetta – Roll 2 – Total Vertical Load versus Time.

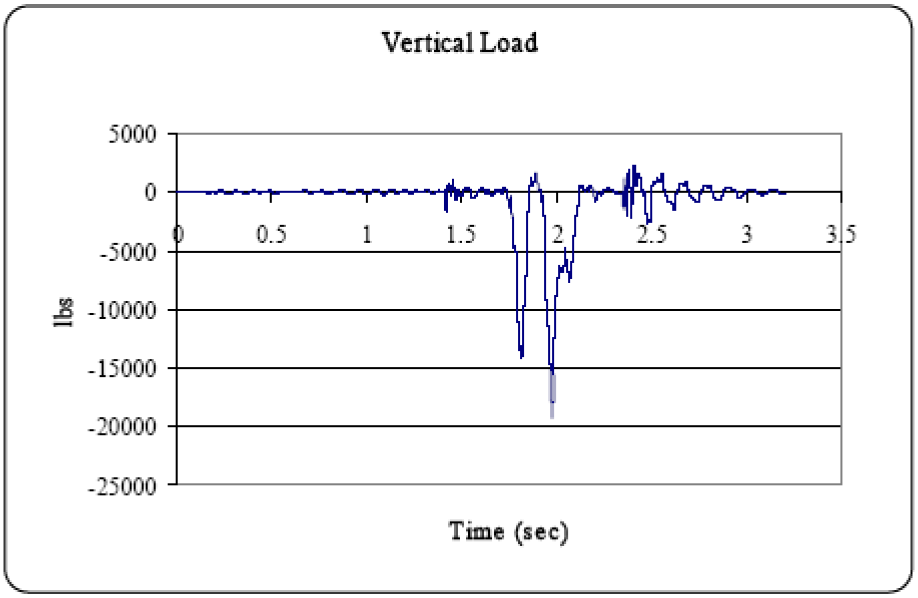

Figure A13. Toyota Camry – Roll 1 – Total Vertical Load versus Time.

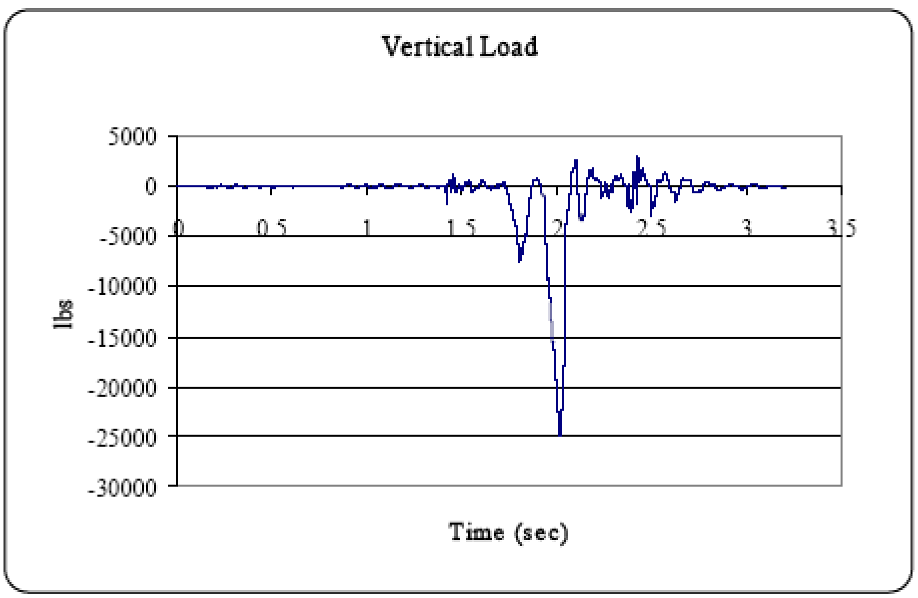

Figure A14. Toyota Camry – Roll 2 – Total Vertical Load versus Time.

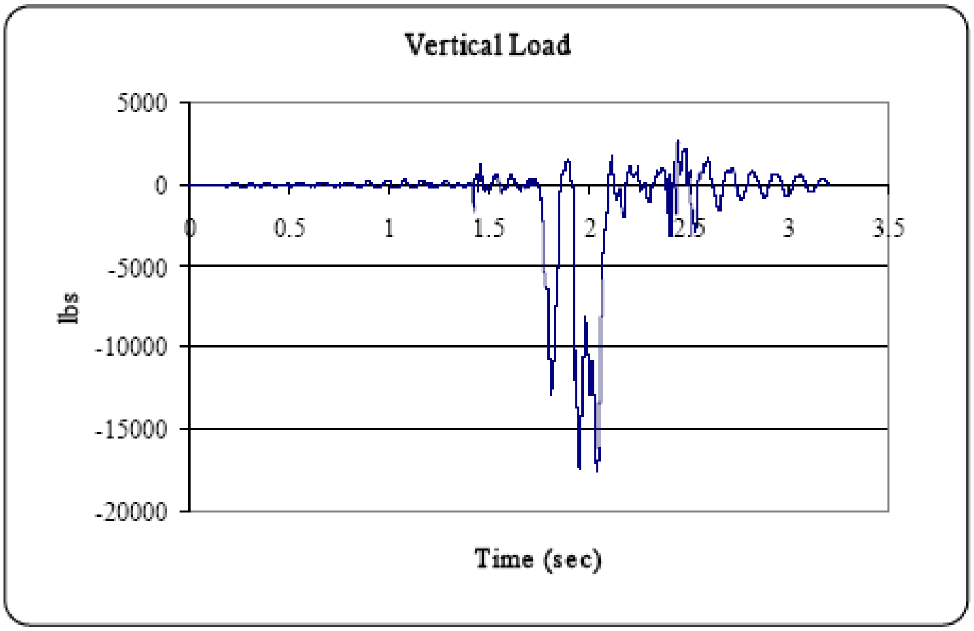

Figure A15. Hyundai Sonata – Roll 1 – Total Vertical Load versus Time.

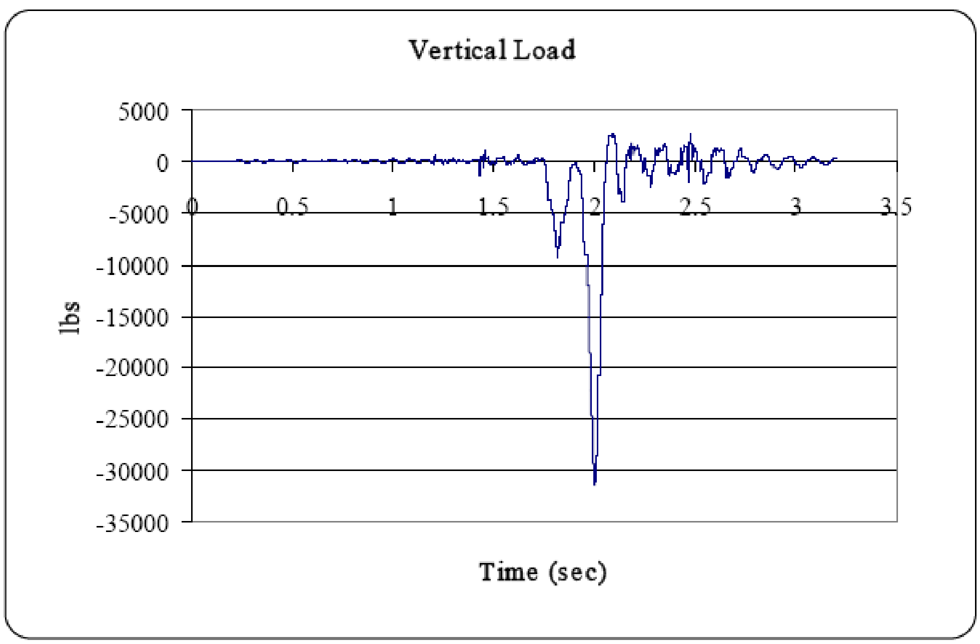

Figure A16. Hyundai Sonata – Roll 2 – Total Vertical Load versus Time.

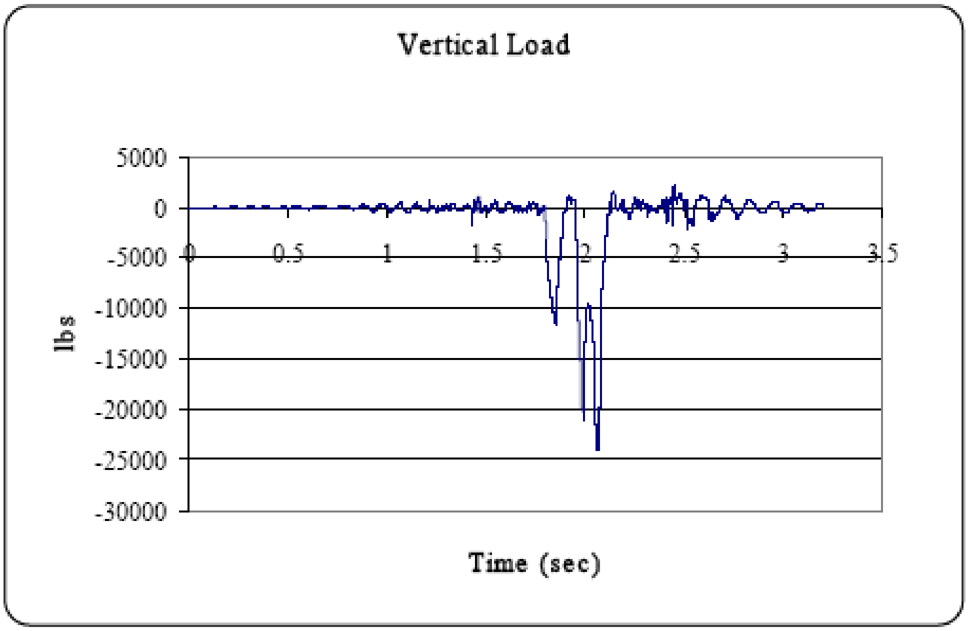

Figure A17. Chrysler 300 – Roll 1 – Total Vertical Load versus Time.

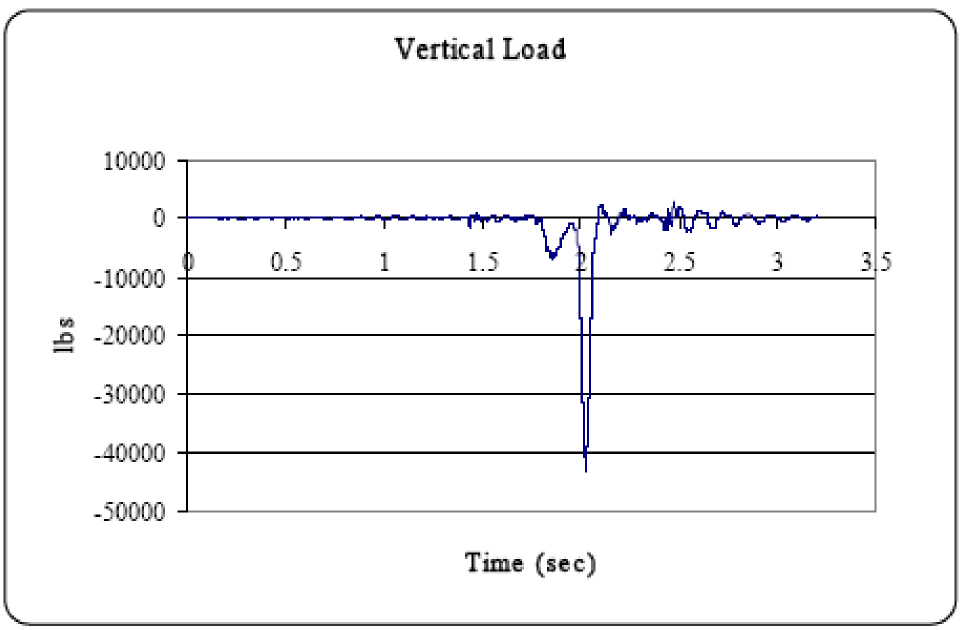

Figure A18. Chrysler 300 – Roll 2 – Total Vertical Load versus Time.

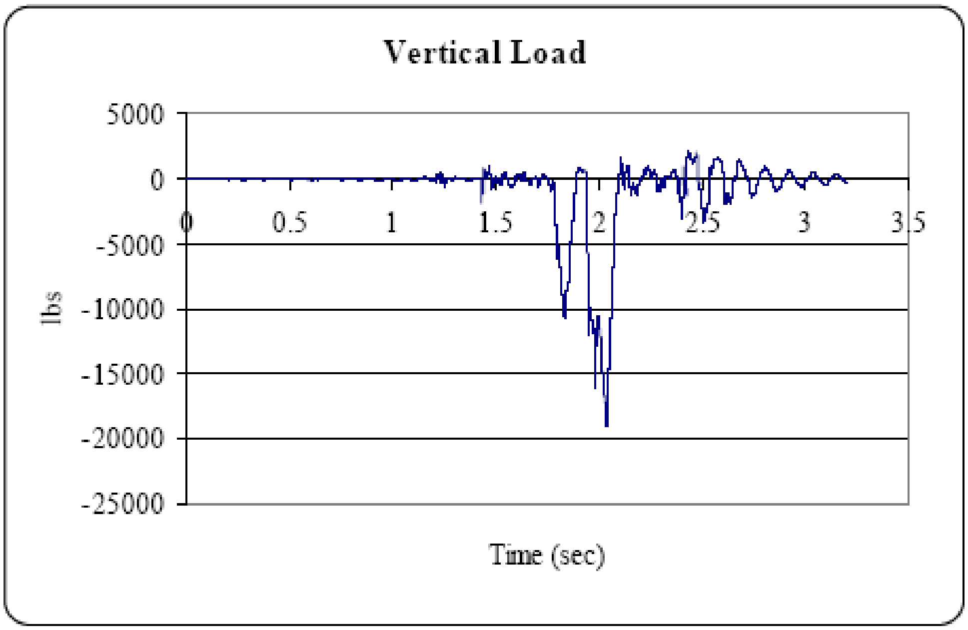

Figure A19. Pontiac G6 – Roll 1 – Total Vertical Load versus Time.

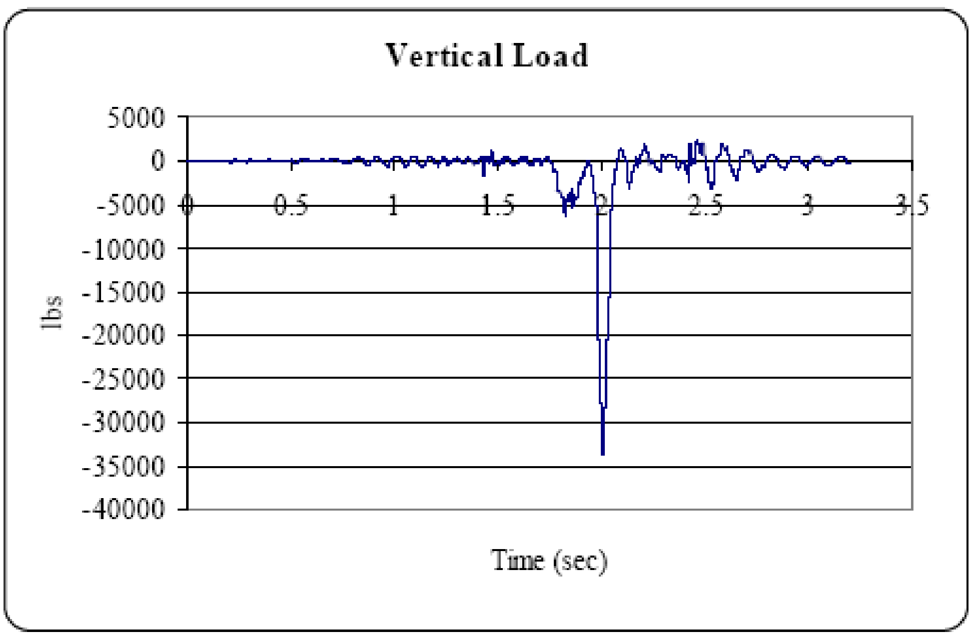

Figure A20. Pontiac G6 – Roll 2 – Total Vertical Load versus Time.

Appendix B. **FMVSS 216, Roof Crush Resistance**

Federal motor vehicle safety standard 216 was originally proposed in 1970. The engineer who was responsible for the proposal intended that it be a non-destructive test because he assumed that the roof strength would be sufficient to resist a force of 1½ times the vehicle's weight without significant damage to the vehicle.[12]

The original test applied a force to the front corner of the roof at a roll angle of 25º and a pitch angle of 10º using a padded (to protect the vehicle's paint) 1 foot square platen. If the vehicle could resist with a force of at least 1½ times the vehicle weight before deforming 5 inches, and could do so sequentially on the second side of the roof, it would pass the standard.

After strong objections from the U.S. automakers, NHTSA agreed to adopt the test conditions defined in Society of Automotive Engineers (SAE) Recommended Practice J374 which reduced the pitch angle to 5º, extended the platen well rearward beyond the B pillar, and required testing on only one side of the roof (See Appendix C). Whereas virtually none of the vehicles currently in production could meet the proposed standard, most could meet the revised version that was issued as FMVSS 216 in 1971.

The Center for Injury Research has constructed its own static test device called the M216. In tests of a number of production vehicles using the M216 using essentially the originally proposed test conditions, it was found that the crush resistance of a roof when measured at a 10º pitch angle is roughly only half that when measured at a 5º pitch angle. This is because at 5º, the resistance comes roughly equally from both the A and B pillars whereas at 10º, the A pillar area must provide virtually all of the crush resistance.

If NHTSA adopts a two-sided test at 5º pitch and 25º roll, with a minimum crush resistance of 3 times a vehicle's weight, that would be roughly equivalent to the original requirement of 1½ times a vehicle's weight at 10º pitch and 25º roll. If NHTSA issues the amended standard with these minimal test conditions, it would mean that we have made no progress from the standard proposed nearly 40 years ago.

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[12] Chu, William H.K., Letter to Rae Tyson, National Highway Traffic Safety Administration, Rochester Hills, Michigan: April 20, 2004 (Docket NHTSA-1099-5572-96).

Appendix C. **NHTSA Press Release on FMVSS 216 from 1971**

DEPARTMENT OF TRANSPORTATION NEWS
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

WASHINGTON, D.C. 20590

FOR RELEASE SATURDAY P.M.
December 11, 1971

NHTSA -- 109-71
Tel. 202-426-9550

The Department of Transportation today issued a new Federal Motor Vehicle Safety Standard that requires passenger cars to have stronger roofs. The new Standard, No. 216, should considerably reduce the number of deaths and serious injuries in rollover accidents when the roof collapses into the passenger compartment.

Specifically, the roof crush standard will provide protection in rollover accidents by improving the integrity of the door, side window and windshield retention areas. It preserves the overall structure of the vehicle in a crash, and decreases the likelihood of occupant ejection.

The new standard, written by the National Highway Traffic Safety Administration, establishes minimum strength requirements for the forward section of the roof. It requires a static test procedure in which a device is pressed downward on the roof until a force of 1 1/2 times the weight of the vehicle, or 5,000 pounds (whichever is less), is reached. During the test, the roof may show no more than five inches of intrusion, as measured by the movement of the test device.

The new standard is intended as an alternative to Standard No. 208 rollover test, and will become effective on August 15, 1973. After August 15, 1977, Standard 216 will no longer be a substitute for rollover test of Standard 208, and is expected to be revoked by then.

The new standard will apply to all passenger cars, with the exception of convertibles.

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